

The distribution of cosmic-ray sources in the Galaxy, γ -rays and the gradient in the CO-to-H₂ relation

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Abstract. We present a solution to the apparent discrepancy between the radial gradient in the diffuse Galactic γ -ray emissivity and the distribution of supernova remnants, believed to be the sources of cosmic rays. Recent determinations of the pulsar distribution have made the discrepancy even more apparent. The problem is shown to be plausibly solved by a variation in the $W_{\text{CO-to-}N(\text{H}_2)}$ scaling factor. If this factor increases by a factor of 5–10 from the inner to the outer Galaxy, as expected from the Galactic metallicity gradient and supported by other evidence, we show that the source distribution required to match the radial gradient of γ -rays can be reconciled with the distribution of supernova remnants as traced by current studies of pulsars. The resulting model fits the EGRET γ -ray profiles extremely well in longitude, and reproduces the mid-latitude inner Galaxy intensities better than previous models.

Key words. gamma rays – Galactic structure – interstellar medium – cosmic rays – supernova remnants – pulsars

1. Introduction

The puzzle of the Galactic γ -ray gradient goes back to time of the COS-B satellite (Bloemen et al., 1986; Strong et al., 1988); using HI and CO surveys to trace the atomic and molecular gas, the Galactic distribution of emissivity per H atom is a measure of the cosmic-ray (CR) flux, for the gas-related bremsstrahlung and pion-decay components. However the gradient determined in this way is much smaller than expected if supernova remnants are the sources of cosmic rays, as is generally believed. This discrepancy was confirmed with the much more precise data from EGRET on the COMPTON Gamma Ray Observatory, even allowing for the fact that inverse-Compton emission (unrelated to the gas) is more important than originally supposed (Strong et al., 2000). A possible explanation of the small gradient in terms of cosmic-ray propagation, involving radial variations of a Galactic wind, was recently put forward by Breitschwerdt et al. (2002); this paper includes a useful literature review on the subject to which the reader is referred.

However the derivation of the Galactic distribution of supernova remnants is subject to large observational selection effects, so that it can be argued that the discrepancy is not so serious. But other tracers of the distribution of SNR are available, in particular pulsars; the new sensitive Parkes Multibeam survey with 914 pulsars has been used by Lorimer (2004) to derive the Galactic distribution, and this confirms the concentration to the inner Galaxy. Fig 1 compares the pulsar distribution from Lorimer (2004) with a CR source distribution which fits the EGRET γ -ray data (Strong et al., 2000). If the pulsar distribution indeed traces the SNR, then there is a serious discrepancy with γ -rays. The distribution of SNR given by Case & Bhattacharya (1998) is not so peaked, but the number of known SNR is much less than the number of pulsars and the systematic effects very difficult to account for (Green, 1996). But even this flatter distribution is hard to reconcile with that required for γ -rays. Another, quite independent, tracer of the SNR distribution is the 1809 keV line of ²⁶Al; whether this originates mainly in type II supernovae or massive stars is not important in this context, since both trace star-formation/SNR. The COMPTEL ²⁶Al maps (Knödseder et al., 1999; Plüschke et al., 2001) show that the emission is very concentrated

to the inner radius of the Galaxy. The ^{26}Al measurements are not subject to the selection effects of other methods; although they have their own uncertainties, they support the type of distribution which we adopt in this paper. The density of free electrons shows a similar distribution (Cordes & Lazio, 2003).

A major uncertainty in the models of diffuse Galactic γ -ray emission is the density and distribution of molecular hydrogen, as traced by the integrated intensity of the $J = 1-0$ transition of ^{12}CO , W_{CO} . Gamma-ray analyses have in fact provided one of the standard values for the scaling factor $X_{\text{CO}} = N(\text{H}_2)/W_{\text{CO}}$ ¹; with only the assumption that cosmic-rays penetrate molecular clouds freely, the γ -ray values are free of the uncertainties of other methods (e.g. those based on the assumption of virialization). However previous analyses, e.g. Strong & Mattox (1996); Hunter et al. (1997); Strong et al. (2000), have usually assumed that X_{CO} is independent of Galactocentric radius R , since otherwise the model has too many free parameters. But there is now good reason to believe that X_{CO} increases with R , both from COBE studies (Sodroski, 1995, 1997) and from the existence of a Galactic metallicity gradient combined with the strong inverse dependence of X_{CO} on metallicity in external galaxies (Israel, 1997, 2000).

A rather rapid radial variation of X_{CO} is expected, based on a metallicity gradient in $[\text{O}/\text{H}]$ of 0.04-0.07 dex/kpc (Hou et al., 2000; Deharveng et al., 2000; Rolleston et al., 2000; Smartt, 2001; Andrievsky et al., 2002) and the dependence of X_{CO} on metallicity in external galaxies: $\log X_{\text{CO}} \propto -2.5 [\text{O}/\text{H}]$ (Israel, 1997, 2000), giving $X_{\text{CO}} \propto 10^{(-1.4 \pm 0.04)R}$, amounting to a factor 1.3-1.5 per kpc, or an order of magnitude between the inner and outer Galaxy.²

A less rapid dependence, $\log X_{\text{CO}} \propto -1.0 [\text{O}/\text{H}]$, was found by Boselli et al. (2002), which however still implies a significant $X_{\text{CO}}(R)$ variation. Boissier et al. (2003) also combine the metallicity gradient with $X_{\text{CO}}(Z)$ within individual galaxies, to obtain radial profiles of H_2 , and give arguments for the validity of this procedure. Digel et al. (1990) found that molecular clouds in the outer Galaxy ($R \sim 12$ kpc) are underluminous in CO, with X_{CO} a factor 4 ± 2 times the inner Galaxy value. Sodroski (1995, 1997) used a similar variation ($\log X_{\text{CO}}/10^{20} = 0.12R - 0.34$) when modelling dust emission for COBE data. Papadopoulos et al. (2002) and Papadopoulos (2004) discuss the underestimation of H_2 using ^{12}CO in the metal-poor outer parts of spiral galaxies.

Fig 2 illustrates some of the possible X_{CO} variations implied by these studies. For the cases where metallicity is

¹ units: molecules $\text{cm}^{-2}/(\text{K km s}^{-1})$

² The values given by Israel (1997, 2000) include the effects of the radiation field, implicitly containing the radiation field/metallicity correlation of his galaxy sample. X_{CO} is positively and almost linearly correlated with radiation field, so the dependence of X_{CO} for constant radiation field is even larger: $\log X_{\text{CO}} \propto -4 [\text{O}/\text{H}]$ (Israel, 2000). By adopting the coefficient -2.5 we implicitly assume the same radiation/metallicity correlation within the Galaxy as over his galaxy sample.

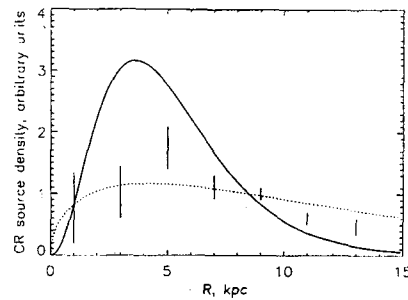


Fig. 1. Cosmic-ray source density as function of Galactocentric radius. Dotted: as used in Strong et al. (2000), solid line: based on pulsars (Lorimer, 2004) as used in this work, vertical bars: SNR data points from Case & Bhattacharya (1998). Distributions are normalized at $R = 8.5$ kpc.

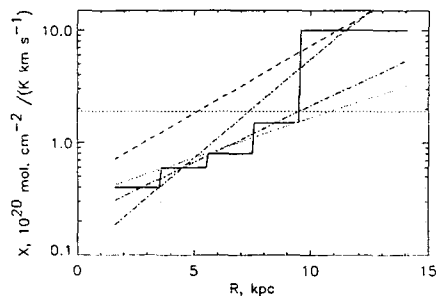


Fig. 2. X_{CO} as function of Galactocentric radius R . Dotted horizontal line, black: as used in Strong & Mattox (1996); Strong et al. (2000); solid line, black: as used for γ -rays in this work; dashed, dark blue: from Sodroski (1995); dash-dot, red: using metallicity gradient as described in the text, $X_{\text{CO}} \propto Z^{-2.5}$ (Israel, 2000), two lines for $[\text{O}/\text{H}] = 0.04$ and 0.07 dex/kpc; dash-dot-dot, light blue: using $X_{\text{CO}} \propto Z^{-1.0}$ (Boselli et al., 2002) and $[\text{O}/\text{H}] = 0.07$ dex/kpc. The values using metallicity are normalized approximately to those from the γ -ray analysis.

used to estimate X_{CO} , the values are normalized approximately to the values used in the present γ -ray analysis, since we are only interested in comparing the variations of X_{CO} .

From the viewpoint of γ -rays, the effect of a steeper cosmic-ray source distribution is compensated by the increase of X_{CO} . Thus we might expect to resolve the apparent discrepancy in the source distribution, and improve our understanding of the Galactic γ -ray emission. In this paper we investigate quantitatively this possibility. Note that the γ -rays include major contributions from interactions with atomic hydrogen and from inverse Compton scattering, both of which are independent of X_{CO} ; this means that the X_{CO} variation has to be quite large to have a significant effect.

2. Data

The EGRET and COMPTEL data are the same as described in Strong et al. (2000, 2004a). The EGRET data consist of the standard product counts and exposure for 30 MeV – 10 GeV, augmented with data for 10 – 120 GeV. The γ -ray point sources in the 3EG catalogue have been removed as described in Strong et al. (2000). The HI and CO data are as described in Moskalenko et al. (2002); Strong et al. (2004a); they consist of combined surveys divided into 8 Galactocentric rings on the basis of kinematic information. Full details of the procedures for comparing models with data are given in Strong et al. (2004a) to which the reader is referred.

3. Model and Method

We use the GALPROP program (Strong et al., 2000, 2004a) to compute the models. GALPROP was extended to allow a variable $X_{\text{CO}}(R)$ to be input. The distribution of cosmic-ray sources is assumed to follow that of pulsars in the form given by Lorimer (2004), as shown in Fig. 1. The other parameters, in particular the cosmic ray nucleon and electron injection spectral shape and propagation parameters, are taken from the ‘optimized model’ of Strong et al. (2004a). As before the halo height is taken as $z_h = 4$ kpc, and the maximum radius $R = 20$ kpc. The isotropic background is as derived in Strong et al. (2004b).

The best approach would be to fit the EGRET data with $X_{\text{CO}}(R)$ free, for a given cosmic-ray source distribution. This will be done in future, but in this work we simply wish to demonstrate the possibility to obtain a plausible solution, so the approach adopted is heuristic.

4. Results

We optimized the model for the assumed source distribution by varying $X_{\text{CO}}(R)$, shown in Fig 2. The electron flux has been scaled down by a factor 0.7 relative to Strong et al. (2004a) to obtain an optimal fit. Figs 3 and 4 show the longitude and latitude distributions for 1 – 2 GeV, compared to EGRET data.

A rather rapid variation of X_{CO} is required to compensate the CR source gradient, but it is fully compatible with the expected variation based on metallicity gradients and the COBE result, as described in the Introduction.

The longitude and latitude fits are good except in the outer Galaxy where the prediction is rather low. One possible reason for this is that the CR source density does not fall off so fast beyond the Solar circle as given by the adopted pulsar distribution, which has an exponential decay.

We have chosen the range 1 – 2 GeV for the profiles since this is where the gas contribution and hence the effect of X_{CO} is maximal. An exhaustive comparison of profiles in all energy ranges is beyond the scope of this Letter, but in fact the agreement is good at all energies.

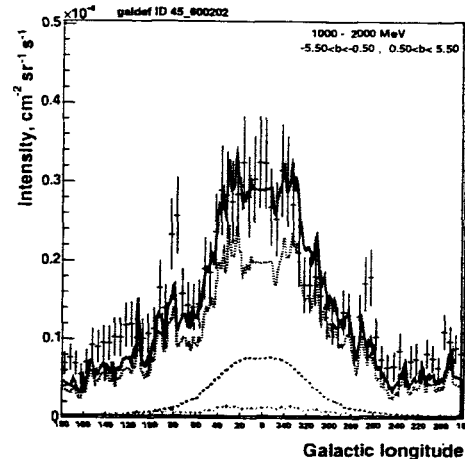


Fig. 3. Longitude profile of γ -rays for 1000-2000 MeV, averaged over $|b| < 5.5^\circ$. Vertical bars: EGRET data; lines are model components convolved with the EGRET point-spread function: green: inverse Compton emission, red: π^0 -decay, light blue: bremsstrahlung, dark blue: total

The larger cosmic-ray gradient in this model has another consequence: the predicted inverse-Compton emission in the inner Galaxy produces more intense emission at intermediate latitudes where the interstellar radiation field is still high; this is precisely the region where previous models (Hunter et al., 1997; Strong et al., 2000, 2004a) have had problems to reproduce the EGRET data.

Fig 5 shows the model spectrum of the inner Galaxy compared with EGRET data; the fit is similar to that of models (Strong et al., 2004a) with *ad hoc* source gradient and constant X_{CO} . The prediction is rather high above 20 GeV, due to the effect of the CR gradient giving an increased IC component; however the EGRET data are least certain in this range (Strong et al., 2004a), so this is not a serious problem.

5. Discussion

We have shown that a good fit to the EGRET data is obtained with the particular combination of parameters chosen. We can however ask whether the pulsar source distribution combined with a constant X_{CO} could also give a good fit if we reduce the CR electron intensity, to suppress the inner Galaxy peak from inverse Compton emission. This can indeed reproduce the longitude profile in the inner Galaxy, but fails badly to account for the latitude distribution, since it has a large deficit at intermediate latitudes. Some variation of X_{CO} is therefore required.

The suggested variation of X_{CO} would have significant impact on the Galactic H_2 mass and distribution. This will be addressed in future work.

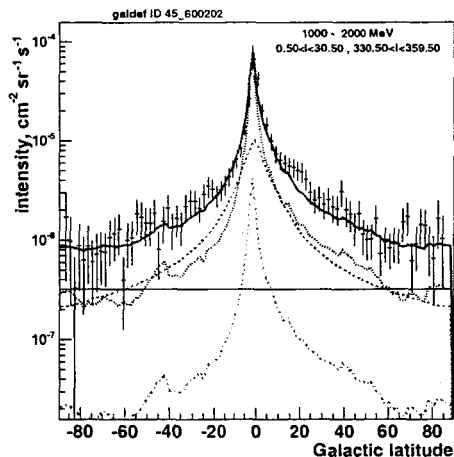


Fig. 4. Latitude profile of γ -rays for 1000-2000 MeV, averaged over $330^\circ < l < 30^\circ$. Data and curves as in Fig 3. In addition, extragalactic background is shown as black horizontal line.

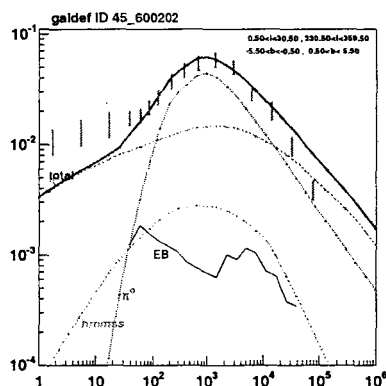


Fig. 5. Spectrum of inner Galaxy, $330^\circ < l < 30^\circ$, $|b| < 5.5^\circ$. Vertical bars: EGRET data (red), COMPTEL data (green). Curves: predicted intensities; inverse Compton (green), π^0 -decay (red), bremsstrahlung (light blue), extragalactic background (black), total (dark blue).

6. Conclusions

Two *a priori* motivated developments allow us to obtain a more physically plausible model for Galactic γ -rays, simultaneously allowing a CR source distribution similar to SNR as traced by pulsars and an expected variation in the $W_{\text{CO-to-}N(\text{H}_2)}$ conversion factor. Obviously the uncertainty in both the source distribution and X_{CO} are large so our solution is far from unique, but it demonstrates the possibility to obtain a physically-motivated model without resorting to an *ad hoc* source distribution. This result supports the SNR origin of CR. The resulting model also gives improved predictions for γ -rays in the inner Galaxy at mid-latitudes.

We have therefore achieved a step towards a better understanding of the diffuse Galactic γ -ray emission. This

result is important input to the development of models for the upcoming GLAST mission.

This Letter is intended only to point out the potential importance of the effect and give a sample application. The next step will be a more quantitative analysis to derive $X_{\text{CO}}(R)$ from the γ -ray data themselves, and then to incorporate this into future modelling efforts.

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